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Edwards Street Laboratory
Yale University
New Haven, Connecticut

ESL Technical Memorandum No. 34
(ESL:424: Ser. 04)
29 March 1954

The Validity of the Transmission Line Model for Determining the Magnetic Field Around Non-Insulated Lines Immersed in Sea Water

A.A. Evett

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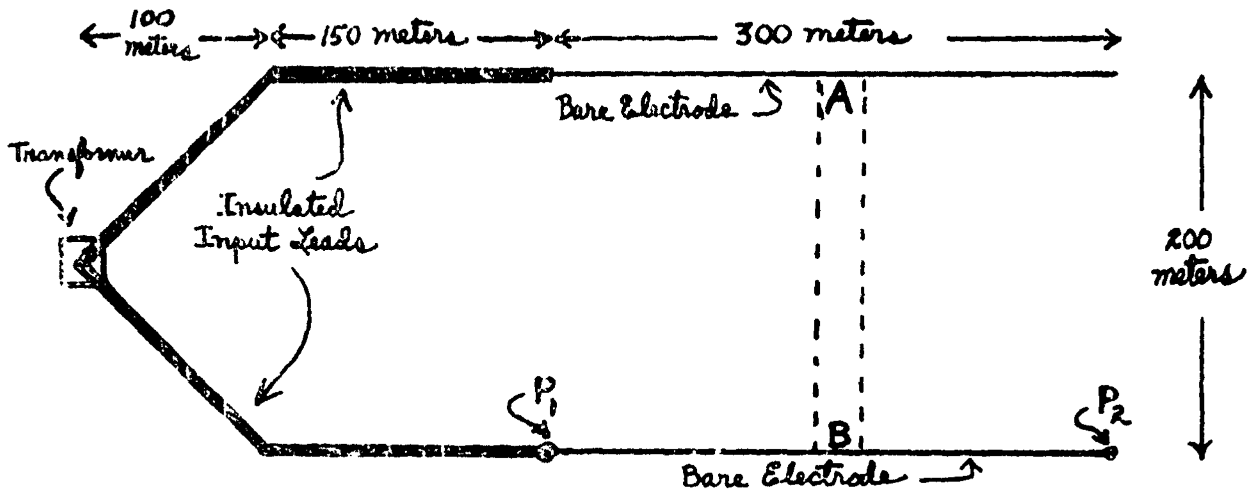
Technical Memoranda are issued as informal internal memoranda on matters of limited interest to give preliminary or interim information which may later be embodied in a more formal report by this Laboratory. They do not necessarily represent the final views of the project nor are they to be regarded as definitive.

1. Brief Outline of the Proposed Model

In Technical Report No. 12 by D.D. Foster the problem of the electric current flow in a semi-infinite conducting strip with a source and sink at one edge was solved for the dc case. These results were used subsequently as a guide for predicting the orders of magnitude of the electromagnetic fields around two bare linear electrodes placed in sea water.

In an attempt to extend the results to a 30 cycle/sec ac frequency M.S. Steinberg, who was an Assistant in Research at ESL from 15 Sept. 1952 - 31 Oct. 1953, set up a theoretical transmission line model for the electrode configuration used in the experimental tests at Beavertail. On the basis of the theoretical model Steinberg developed equations for the magnetic field; however, numerical results were not obtained by Steinberg because the questionable status of the validity of the model did not seem to warrant the considerable effort required to perform the numerical integrations.

A sketch is given on the next page of the plan view of the configuration used in the transmission line model to approximate the actual experimental arrangement. The system was assumed to rest on the bottom beneath 10 meters of sea water.



The magnetic field was considered to arise from three different current distributions:

(a) Current in the insulated input leads. The current should have nearly the same amplitude and phase throughout the entire length of the input leads because of the low attenuation along the <u>insulated</u> wire.

(b) Current in the bare electrodes. The amplitude of this current should decrease with increasing distance from the input end. The voltage and current distribution along the bare line was determined from the standard transmission line equations.

(c) Current in the sea water. The instantaneous current distribution was assumed to be such that the current flow was at all times perpendicular to the bare electrodes. The dc theory was assumed adequate to give the instantaneous current between two points on opposite sides of the line (e.g. points A and B in the sketch) in terms of the instantaneous voltage between these two points. These assumptions are consistent with the use of the transmission line equations to give the current distribution along the bare electrodes as mentioned in (b).

On the basis of the above model a frequency of 30 cycles/sec gives a wave length along the line of about 1100 meters. The damping of the wave is considerable; the voltage and current amplitudes at the far end of the line are only about .08 of the amplitude at the input end.

2. Discussion of the Assumptions Used in the Transmission Line Model

Several objections can be made against applying the transmission line equations to the situation under discussion. The following objections will be discussed:

(1) The speed of a wave in sea water is so slow that the separation of the lines may be a non-negligible fraction of the wave length of a 30 cycle/sec signal propagated from one line across to the other. More technically, the "near zone condition" may not be satisfied (see page 80 in King, Mimno, and Wing, Transmission Lines, Antennas and Wave Guides).

(2) The model neglected the terminal impedance of the line and neglected the reflected wave.

(3) The current in the sea water was assumed to flow perpendicular to the line. However, the short wave length predicted by the transmission line equations implies that the variation of potential along the line is nearly as great as that between two points opposite each other on the two lines (points A and B for example). Therefore one would expect a considerable fraction of the current flow to be between two points on the same line as well as from one line to the other.

Objection (1) is not serious because the signal velocity for a wave in shallow water is much greater than for a wave in the corresponding infinite three-dimensional medium. The time required for a signal at one point on the bottom to reach another point on the bottom is given by the time required for the signal to go to the surface at the speed characteristic of the sea water, travel through the air at the speed characteristic of the air (this speed being much greater than for the sea water), and then to travel from the surface straight down to the point on the bottom. Thus, in the model the time lag is given essentially by the time required for the wave to traverse 20 meters of water instead of the 200 meters separating the lines.

The attenuation of the wave along the line is so great that the neglect of the terminating impedance should be of little importance. The voltage and current amplitudes drop off so rapidly with distance that the nature of the transmission line in regions not near to the input end could have only a secondary effect.

However, Objection (3) is valid and is of extreme importance, not only because it casts doubt on the procedure for obtaining the instantaneous current distribution in the sea water, but also because it points out an essential flaw in the use of the transmission line equations to obtain the current and voltage distribution in the lines. The use of the concepts of inductance, capacitance, and conductance per unit length of transmission line remains legitimate only under conditions where the wave length along the line is large compared to the separation of the lines, even if the "near zone condition" is satisfied. Otherwise the voltage variation along the line introduces large modifying effects which are neglected completely in the transmission line approach to wave propagation.

3. Numerical Check of the Transmission Line Model

The rigorous procedure for solving for the field distribution would be to treat the problem by antenna theory. Antenna theory is very unwieldy for the comparatively simple ordinary situations; the present problem would be more intractable because even the basic theory of radiation in a conducting slab is largely undeveloped. Some work has been done on the electromagnetic field emitted by a radiating dipole located in a conducting half space. (See Baños and Wesley, The Horizontal Electric Dipole in a Conducting Half Space, Scripps Institution of Oceanography, Reference 53-33, September 1953, for a comprehensive summary of the present status of this radiation problem.) Approximate results are available for the field at very large distances from the dipole, and also for the field at points close to the dipole compared with a wave length. The region of interest in the configuration under consideration is of the order of one wave length from the radiating source so neither approximation is applicable.

The difficulty in obtaining quantitative results by a rigorous theory places some importance on the question as to whether the transmission line model, in spite of its shortcomings, yields results of semi-quantitative validity. Some of the expermental data obtained at Beavertail could be checked against the results predicted by the model without performing all the numerical integrations required for the total solution. How this was done is described in the following paragraph.

According to the model the horizontal component of the magnetic field perpendicular to the lines should have no contribution from the current distributed throughout the sea water. The values of this component at the surface of the water at points P_1 and P_2 (refer to the sketch) were calculated by numerical integration of the appropriate equations developed by Steinberg. The amplitude of the current in the input leads enters as a parameter in the results and is not known definitely from the available experimental data. However, a value of this parameter was selected so as to give agreement between the theoretical and the experimental values of the magnetic field at the point P_1. Substitution of the same parametric value in the expression for the field at P_2 gave a theoretical result which was a factor of about 7 larger than that obtained experimentally. This large discrepancy, although not at all conclusive, indicates that the model is not useful even for semi-quantitative purposes.

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